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ABSTRACT. Hills eroded by floods of glacial meltwater in Swedish Lapland resemble streamlined erosional features on Mars. The morphology and materials indicate a similar origin for the features on both planets. The Båldakatj area can be considered a terrestrial analog for Martian landforms; this similarity suggest that other features in Lapland, including boulder deltas, may also occur on Mars.

Introduction

This study describes fluvioglacial features in Swedish Lapland that seem to be analogous to certain features on Mars and compares them to streamlined erosional remnants on Mars.

Erosional remnants on Mars

The exploration of Mars has revealed a suite of landforms on the surface of that planet that appear to be fluvial in origin. Streamlined erosional remnants occur in many of the Martian "outflow" channels that are found in the equatorial region (zone between 30° N and S latitude) of Mars (Mars Channel Working Group 1983). The channels appear as full streams, with few or no tributaries; they may have developed from melting ground ice or artesian outflows. These residual hills seem to be mostly eroded from bedrock or alluvium, although some may be depositional in origin (Baker and Kochel 1979; Mars Channel Working Group 1983).

Terraces or benches around the Martian features have been interpreted as evidence of either differential erosion of strata (Masursky *et al.* 1977; Baker and Kochel 1978a) or erosion of bedrock material (Mars Channel Working Group 1983). Some of the streamlined forms have developed downstream of craters or other flow obstructions, and some have crescentic depressions near the upstream end (Fig. 1).

Previously suggested terrestrial analogs

One of the most useful ways to study the surfaces of other planets is to compare them with landforms on Earth that appear to be analogous. The similarities and differences between features on the two planets often reveal important aspects of their nature and origin. The Martian streamlined islands have frequently been compared to the Channeled Scabland of eastern Washington, USA (Baker and Nummedal 1978). This area of Washington State includes features that resemble nearly all of the forms found in Martian outflow channels (Mars Channel Working Group 1983). The material into which the Scabland is carved is primarily loess and basalt. The probable origin of the Channeled Scabland, the catastrophic outbreak of glacial Lake Missoula, also provides a useful analog for the origin of the large erosional remnants on Mars (Baker, 1978).

Several other terrestrial analogs have been offered for these Martian features, notably the glacier-dammed lakes of Iceland (Malin 1980) and Canada (Thompson 1980). A major advantage of using modern glacial lakes as analogs is that the formation of the lake and its catastrophic outbreak can be observed directly, rather than inferred from geologic and geomorphic evidence.

The variety of fluvial features on Mars offers convincing evidence for the importance of running water in Martian geomorphic history, but the conditions under which this may have occurred are still unclear. Liquid water cannot exist on the surface of Mars under current conditions; if present, it would either freeze or sublimate into the

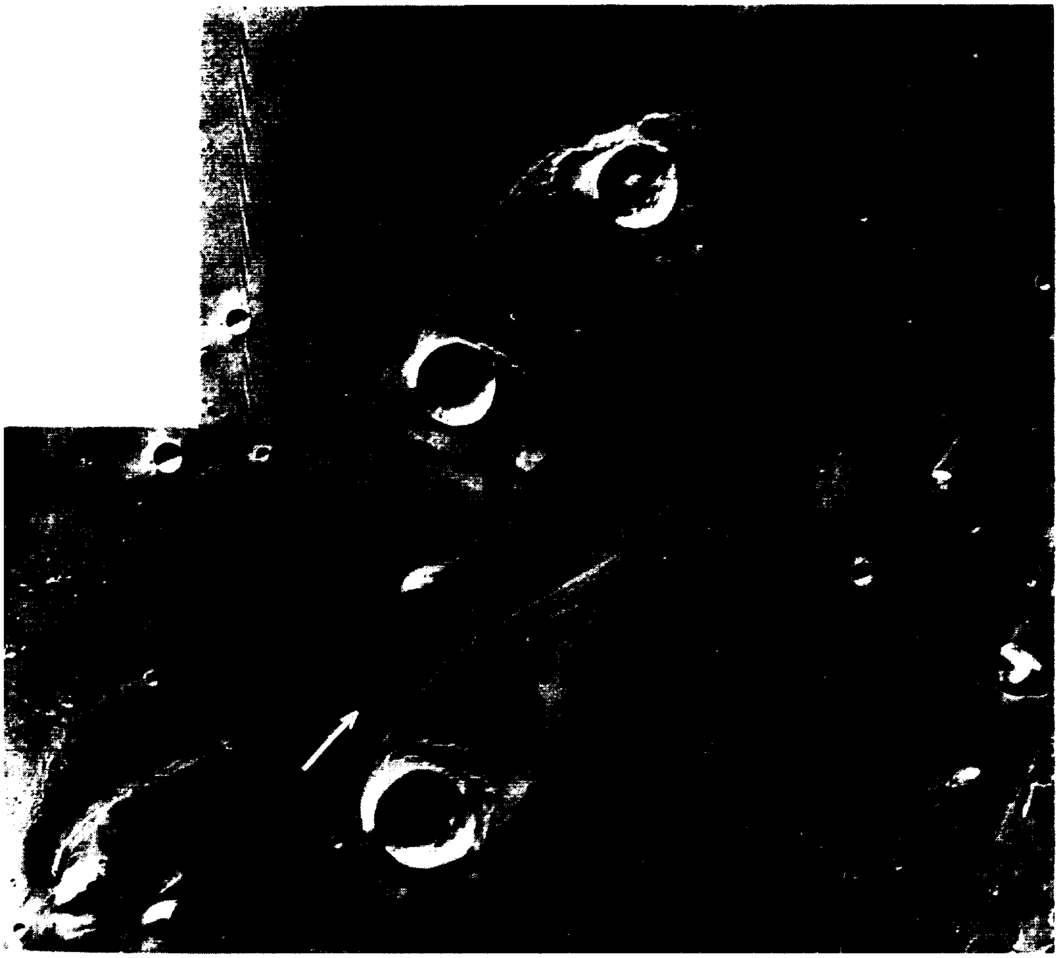

Fig. 1. Streamlined erosional remnants on Mars, at the mouth of Ares Valles near the southern boundary of Chryse Planitia (211–4987; 21N, 31W), (Photo courtesy NASA/Jet Propulsion Laboratory). Presumed paleoflow direction is indicated by the white arrow.

thin Martian atmosphere. The most probable explanation for the formation of the Martian outflow channels is the catastrophic outbreak of water trapped beneath a permafrost zone, possibly released by sudden melting of ground ice (Carr 1979). Other possible factors may have been an earlier episode in Mars' history when the atmosphere was denser and liquid water could persist at the surface, and massive recycling of water in a global aquifer (Clifford 1980). Catastrophic events seem most consistent with the large-scale but localized evidence of running water (Mars Channel Working Group 1983).

Erosional remnants in the Båldakatj area

Geologic setting of the Båldakatj area

The study area with the proposed analogs for Martian landforms is in Swedish Lapland, at 66°N and 18°E. It lies between lakes Bårgåjaure and Båldakatj, about 13 km southwest of Lake Voulvojaure, a part of the present Pite River. The nearest village is Arjeplog (Fig. 2).

The large-scale morphology of the landscape can be described as a monadnock plain, with solitary mountains and hills on a generally flat area. Well-developed valleys are rare (cf Rudberg, 1970). The highest mountains reach 600–800 m a.s.l. The flat, broad valley plains often contain lakes and traces of glaciofluvial activity. The Båldakatj area includes broad areas with alternating bedrock outcrops, till, and coarse-grained sediments. The 4 km wide valley is oriented in a NW-SE direction, approximately parallel to the direction of the last ice movement in the area. The predominant rock type is migmatized granites of Arvidsjaur type (Ödman 1957).

The Båldakatj area has been described in detail by Elfström (1983). In the proximal part of the delta meltwater streams have eroded large channels between streamlined erosional remnants of till (Fig. 3). The central part represents a transitional environment, with several smaller drainage channels, mainly in coarse, poorly sorted, glaciofluvial material. The distal part of the delta has well-defined lobate deposits. Some of these are composed of glacio-fluvial cobbles and boulders, others are composed of till but sculptured by running water. This study will concentrate on the erosional remnants in the proximal part of the area.

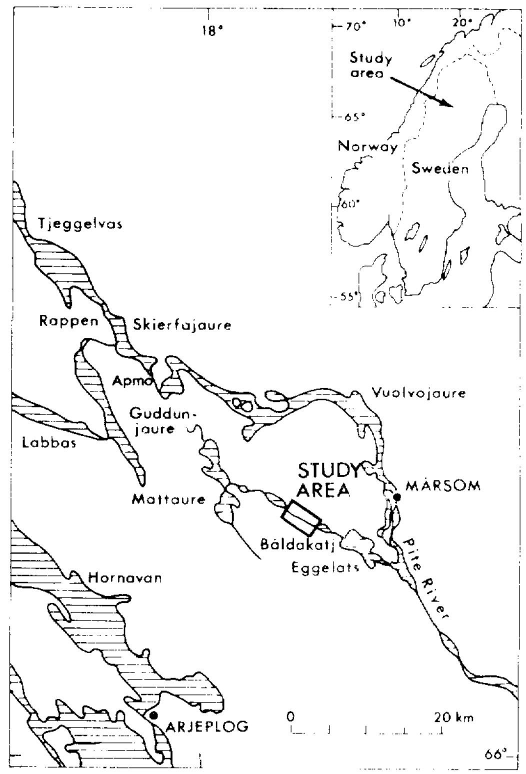

Fig. 2. Location map.

Late glacial drainage in the Båldakatj area

During the inland ice recession in Sweden, about 8000 years ago, large amounts of water flowed in drainage nets that later were partially or totally abandoned. Outwash plains, boulder deltas, channels and other glaciofluvial forms indicate the magnitude of these catastrophic flows along the Pite River valley in northern Sweden (Elfström 1983; Hoppe 1969; Ulfstedt 1979; Sundborg *et al* 1980).

Deglaciation of the area has not been investigated in any detail, but in general the ice-margin retreated towards the northwest. The late glacial drainage from the melting inland ice was concentrated in the valleys that are generally oriented northwest-southeast (cf. Fig. 6 in Elfström 1983). The glacial drainage was particulary active as a geomorphological agent in the upper Pite River valley, as indicated by sediments and eroded bedrock at elevations up to 20 m above the current river level (Daniel 1975).

The erosional remnants and the vast boulder delta at the western edge of Lake Båldakatj are evidence of high discharge. This might have occurred either in one single catastrophic drainage event or during a series of recurrent meltwater floods (Elfström 1983; Williams 1983).

Origin of the erosional remnants

A detailed photogrammetric map of the Båldakatj area was made in 1982 to give an overview of the Båldakatj boulder delta (Elfström 1983). The map presented in Fig. 4 is a part of this contour map.

Fig. 3 shows that meltwater drained primarily through four or five large meltwater channels towards the southeast. In some places, the channels carved down to bedrock. The meltwater channels have left several erosional remnants as elongated, streamlined hills between the channel branches (cf. Figs. 3 and 4).

The streamlined hills appear to be remnants of hummocky moraines that existed prior to the fluvial erosion. Evidence for this interpretation includes 1) hummocky moraines are characteristic of this region and still exist in the immediate vicinity of the streamlined hills, 2) an abundance of boulders, some of which are very large, on the surfaces of several of the hills, and 3) the occurr-


BARGA-
JAURE
434
STOR-
SELET
MATTAUREÄLVEN
BALDAKATJ
404
0
300
600 m

ence of several small lakes between the hills. All these features are characteristic of hummocky moraine areas (Hoppe 1952).

The hummocky hills probably served as flow obstructions that separated the catastrophic flood into several channel branches. This interpretation could also explain the various forms and the different trends of the long axes. The flow was not forceful enough to completely reshape the original hummocky moraine topography into well-defined streamlined forms.

Boulder-rich till is widespread in the Båldakatj area, including most of the surrounding valley sides. Several locations with hummocky or Rogen-type moraine can also be found on the broad valley bottom. Coarse, poorly sorted glaciofluvial material occurs primarily in the bottom of the large channels, and well-sorted cobble and boulder material forms large parts of the boulder delta deposits, located downstream from the channels. The particles in the delta deposit normally range in size from 2 to 50 cm, but boulders with diameters of 1 m can be found.

Morphology of the erosional remnants

The erosional remnants range in shape from purely streamlined to blunt and irregular forms (Fig. 4). They range from 200 to 1000 m in length and 10 to 15 m in height. The best-developed streamlined hills have rounded prows and steep slopes on their upstream end and tapering tails with gentle slopes pointing downstream (Fig. 5).

Evidence of flow phenomena can be found around all remnants. On some, the upstream ends have a concentration of large boulders that formed as an armour (Fig. 6), and material on the downstream part may form a distinct tail. The boulder mantle is widest at the upstream end and gradually disappears just behind the widest part of the hills. The boulders are also sorted within the mantle; the largest boulders are at the base of the hill. Terrace-like benches occur along the sides of some remnants (Fig. 7). The Mars Channel Working Group (1983, p. 1038–39) suggested that, on Mars, "some tails are probably remnant bedrock and not alluvium, as terrace-like benches are common along the downstream edges".

The tops of the streamlined features also have several distinctive characteristics. Remnant 1 has a few boulders on the top, while hills 2 and 7 have large boulders at their upstream ends but very few on their downstream tapering tails. The rest of the remnants have many large boulders on their surfaces. Remnant 1 also has a depression on the top that parallels the long axis of the hill. On the edges of the depression, especially at the upstream end, small streamlined mounds of boulders have been formed.

Some of the streamlined remnants are entirely erosional, but some of the trailing features may be partly depositional. One criterion for this interpretation is the small number of boulders in the downstream tapering tails.

The evidence for a depositional origin of some of the tails is supported by a comparison with the streamlined hills formed during flume experiments carried out by Komar (1983, p. 653). He found that a small triangular region was formed in the immediate lee of the initially circular islands. The streamlined hills 2 and 7 in the Båldakatj area show the same features (Figs. 3 and 4). This could probably also explain the boulder-rich surfaces of

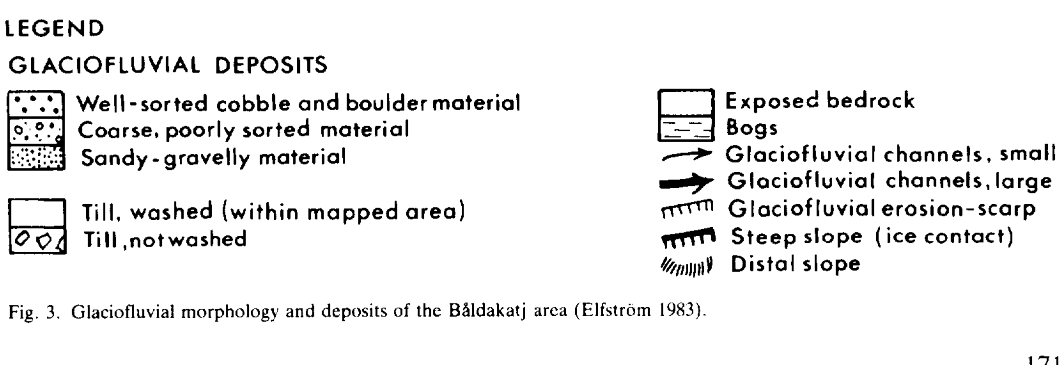

Fig. 3. Glaciofluvial morphology and deposits of the Båldakatj area (Elfström 1983).


0
500 m
1
2
3
4
5
6
7
8
9
400
435
440
445
450
455
430

hills 2 and 7, which may consist of primary till material deposited as hummocky moraine hills. These have served as flow obstacles. Fig. 4 also shows spits around the hills 3 and 4. These spits do not join at the downstream end, probably because of on an insufficient flow discharge or a very rapid decrease of flow (cf. Fig. 3 in Komar, 1983).

The best-developed streamlined form in this area is hill 1. The experiments by Komar (1983, p. 653) show that the most distinct streamlining develops when the water depth is just sufficent to "top" the island, with flow over the island becoming supercritical because of decreased flow depths and high velocities. Field studies of subfluvially eroded loess residuals in the Cheney-Palouse scabland tract (Patton and Baker 1978) show that the erosional residuals have gravel bars attached to their tails (Baker and Kochel 1978b, p. 3195). Bar-like forms occur on the downstream tapering tail of remnant 1.

Streamlined islands in the Båldakatj area may be compared with published maps and photographs from the Channeled Scabland (Bretz 1923; Baker 1973) and Viking photographs and maps from Mars published by Baker and Kochel (1978b) and Mars Working Group (1983). The channels of all three regions contain streamlined erosional remnants.

One way to compare the islands quantitatively is by comparing lemniscate loops (Komar 1983, p. 136). According to Baker and Kochel (1978b, p. 3195), the analysis of streamlined shapes includes three physical measurements: area, length and width. From these data, a dimensionless parameter k can be calculated $k = \frac{L^2\pi}{4A}$ where L is length and A is area. The minimum value of k is 1, which is a circle. Larger values of k are associated with more elongate loops (Komar 1984, p. 134). 175 streamlined hills and bars were measured in the Scablands and 47 streamlined forms were measured on Mars by Baker and Kochel (1978b). The k values in the Scablands range from 1.0 to 8.3, with an average k=3.2; Martian k values range from 1.5 to 12.0 with an average k=3.8. In the Båldakatj area, 9 streamlined forms were measured. The k value ranges from 1.2 to 4.5, with an average k=2.9.

The length (L) vs. width (W) relation serves as an index of elongation. Larger values of the ratio L/W imply greater elongation of the form. In the Scabland streamlined forms, 1 km in length, have L/W = 3.0 while forms with lengths of 100 km have L/W = 4.1 (Baker and Kochel 1978b, p. 3197). The average L/W ratio of the erosional remnants in the Båldakatj area is 2.5. The L/W ratio for the largest remnant is 3.3.

Fig. 5. Aerial photograph of the well-developed erosional remnant No 1. The white arrow shows direction of flow. Published with the permission of Lantmäteriverket (National Land Survey of Sweden) 1985-09-04.

The Båldakatj area as a terrestrial analog

The Båldakatj area is the first Swedish area that has been proposed as a terrestrial analog for Martian fluvial features. Besides introducing another

Fig. 4. Contour map of the erosional remnants at Båldakatj. Contour interval 1 m. Direction of flow towards the lower part of the map. Published with the permission of Lantmäteriverket (National Land Survey of Sweden) 1985-09-04.

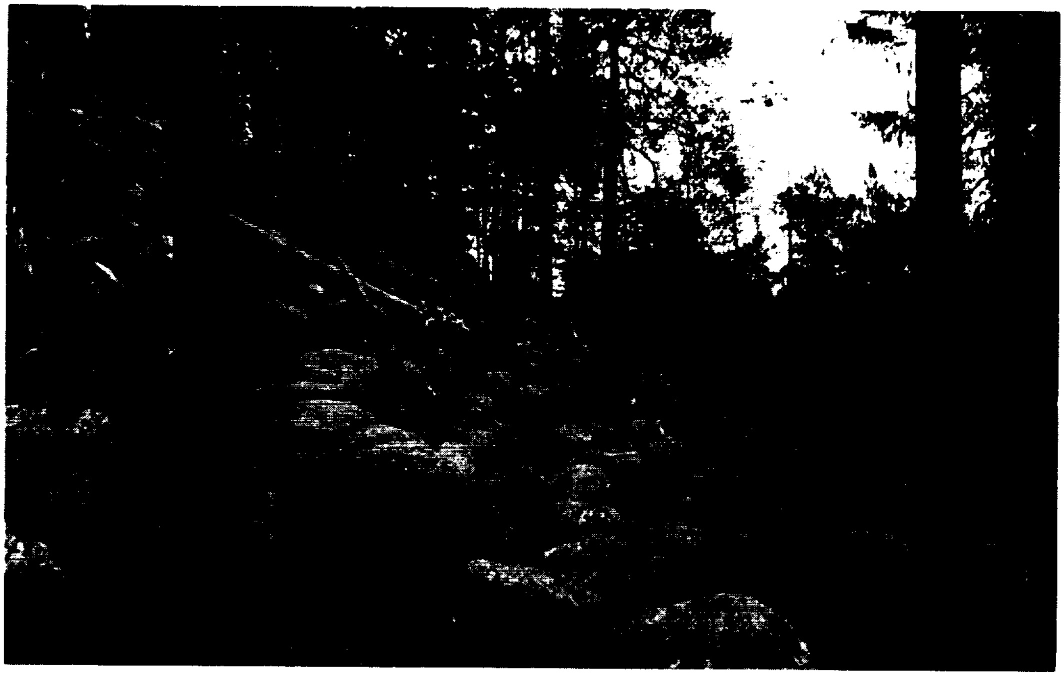

Fig. 6. Erosional remnant No 1 from the ground, showing boulders along its edge. Photo: Åsa Elfström 1984.

Fig. 7. Terrace-like benches occur along the flank of erosional remnant No 6. Terraces can also be found along the flanks of remnant 2, 5 and 8. Photo: Åsa Elfström 1984.

planetary analog within Scandinavia, the identification of Båldakatj as a terrestrial analog also supports a catastrophic flooding origin for the Martian streamlined islands.

The size of the transported material in the Båldakatj area may also represent a closer analog to the Martian conditions than the loess and basalt of the Channeled Scabland. The Båldakatj boulder delta, 2–3 km downstream from the erosional remnants, is covered by material 10–50 cm in diameter. Much of the Martian surface is likely to have similar-sized material, some of it as a product of extensive break-up of the surface materials by meteorite impact. Photogeologic studies of both landing sites for NASA's 1976 Viking mission to Mars show stones (10–20 cm) scattered over the surface.

Although the erosional remnants upstream of the delta range from very streamlined to blunt and irregular in shape (Fig. 4), their form is consistent with the relationships between length, width, and area described by comparision with lemniscate loops (Komar 1984). This evidence alone is not sufficent to prove a fluvial origin for either group of landforms, but does show that the geometry is consistent with this interpretation. However, for other reasons it is quite evident that the Båldakatj delta has a catastrophic origin (Elfström 1983).

Discussion

A recurring problem in the use of terrestrial analogs to study Martian landforms is the difference in the scale of these features between the two planets. Martian features are generally ten times larger or more than similar forms on Earth. In some instances, the difference in size can be explained by the lower gravitational acceleration on Mars (40 % of the value for Earth), but often other factors must be taken into account. For example, the Martian erosional islands are 10–50 km in length (Mars Channel Working group 1983); the streamlined remnants in the Channeled Scabland are 10–30 km in length (Baker 1978). Those in the Båldakatj area are approximately 1 km long. Much of the size difference between the Båldakatj and Martian features appears to reflect the magnitude of the flow, which is difficult to reconstruct for either area. Unfortunately, the area's unknown paleohydrology limits the usefulness of Båldakatj as a terrestrial analog for Mars.

A major strength of the Båldakatj analog lies in the size of the material found there. The poorly sorted till with abundant boulders in Båldakatj may be similar to the near-surface material on Mars, where Viking images and lander experiments have revealed a wide range of grain sizes (Binder *et al.* 1977; Mutch *et al.* 1977). Båldakatj may therefore represent the Martian landforms at least as closely as any previously proposed analog, including the loess and basalt of the Channeled Scabland.

The similarities between the erosional remnants on Mars and in Båldakatj also suggest that Swedish Lapland may offer other analogs for Martian features. The feedback between the studies of the two planets is an important benefit of planetary geology; terrestrial features can help explain Martian landforms, which then encourage more detailed study of the Earth's surface. If the streamlined remnants on Mars are analogs to those in Båldakatj, then we might also expect to find boulder deltas and large isolated debris blocks on Mars. These have never been reported, but no systematic search has ever been made. The discovery of these would certainly lead to renewed investigations of the terrestrial analogs.

Conclusions

The erosional remnants in the Båldakatj area of Swedish Lapland are a terrestrial analog for the streamlined islands in the outflow channels of Mars. The similar morphologies and probable origins by catastrophic flooding support the analog and the boulder-rich till in Båldakatj may be similar to the near-surface material on Mars. The Båldakatj features are an order of magnitude smaller than the Martian landforms, probably because they result from a smaller-scale flood. If the streamlined islands in the Båldakatj area are valid analogs for Mars, then the downstream reaches of Martian outflow channels may also have boulder deltas and large, isolated blocks of transported material, similar to those observed on the Båldakatj delta. The similarities between the erosional remnants in the two places indicate that Swedish Lapland offers a useful analog for landforms on the surface of Mars.

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